REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
9 June 2003

2. REPORT TYPE
View Graphs

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

High Thrust to Weight Bipropellant Reentry Vehicle Thrust Vector Control Thru Micro-Miniaturization

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER
4847

5e. TASK NUMBER
0255

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-VG-2003-153

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-VG-2003-153

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030801 115

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Sheila Benner
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	A		(661) 275-5693

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

FILE

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 09 Jun 2003

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2003-153**
William Figueiredo (AFRL/PRST), "High Thrust to Weight Bipropellant Reentry Vehicle Thrust Vector Control Thru Micro-Miniaturization"

AIAA Joint Propulsion Conference **(Statement A)**
(Huntsville, AL, 20-23 Jul 2003) (Deadline: 20 June 2003)

HIGH THRUST TO WEIGHT BIPROPELLANT REENTRY VEHICLE THRUST VECTOR CONTROL THRU MICRO-MINIATURIZATION

23 July 03

AIAA 2003-5258

Bill Figueiredo

Air Force Research Laboratory

Propulsion Directorate

Edwards AFB, California

High Thrust to Weight Ratio Rocket Propulsion Thru Miniaturization

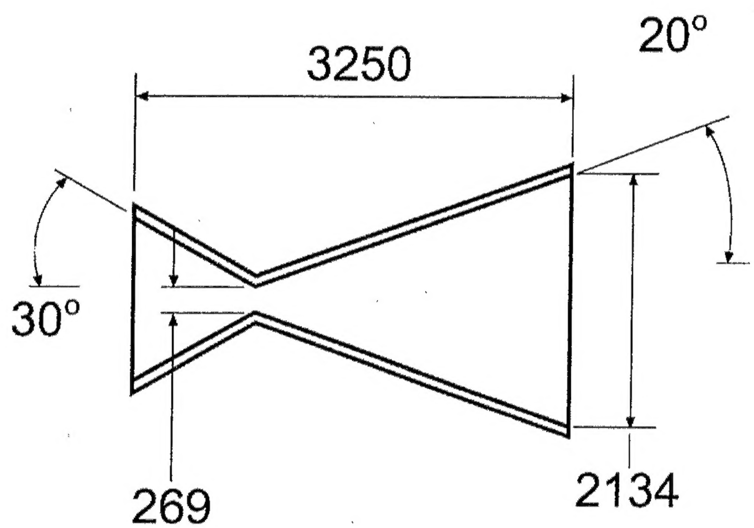
- The extremely high thrust-to-weight ratios achievable with micro-miniaturization are a result of the "cube-square-law".

- As the engine is scaled down linearly, the propellant flow, and thus the power, decreases with chamber cross-sectional area (the square of the linear size) while the weight decreases with the volume of the engine (the cube of the linear size) so that the power-to-weight ratio increases linearly as the engine size is reduced.

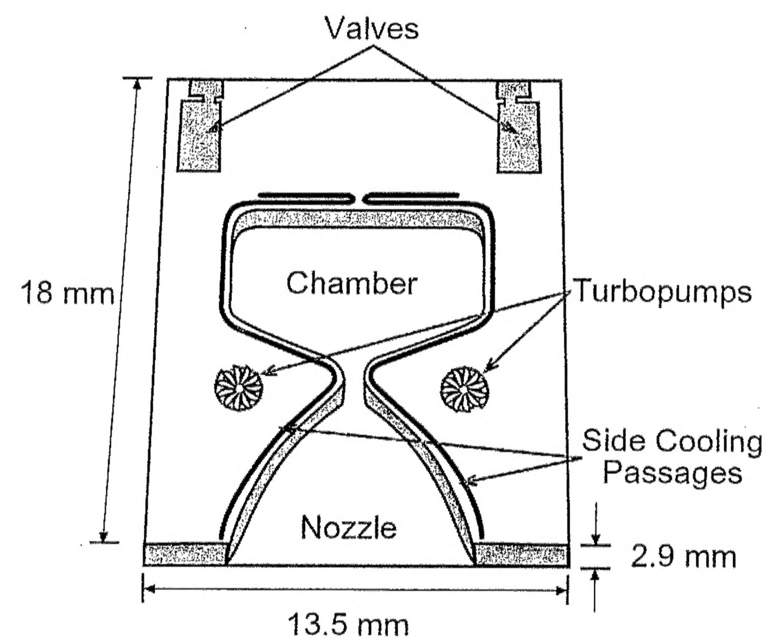
Two Thruster Fabrication Approaches Investigated

- MIT Gas Turbine Lab MEMS bipropellant engine
  - Very sophisticated regen cooled engine
    - Five-hundred hole gaseous bipropellant injection
    - Susceptible to erosion with corrosive hypergolic propellants (Not a problem for short RV missions)
- AFRL Micronozzle
  - Micromachined conical nozzle capable of surviving corrosive hypergols
- Both nozzles are smaller then the size of a dime

Candidate Microthrusters



AFRL Micronozzle Schematic. All Dimensions in μm. (Ketsdever, 1999)



MIT MEMS Bipropellant Engine General Arrangement (London, 2000)

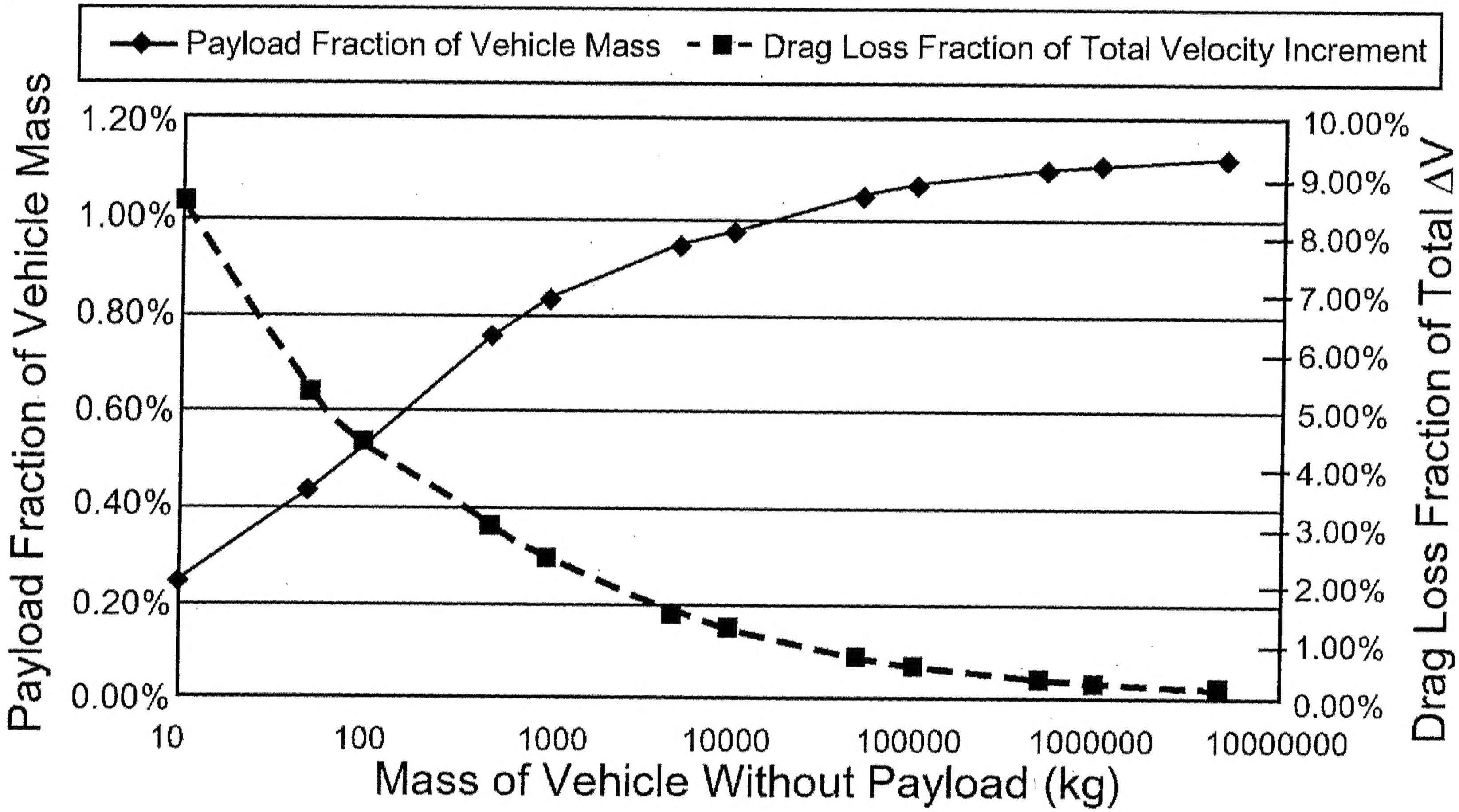
Issues that Diminish Performance at Reduced Rocket Engine Characteristic Lengths

- Shorter combustion residence times required for shorter chamber residence (Theoretically and experimentally addressed by AFRL and MIT)
- Higher heat losses at reduced scales (Recover with regen cooling)

Issues that Diminish Performance at Reduced Rocket Engine Characteristic Lengths-Cont.

- Higher aerodynamic losses associated with small scale rocket vehicle
  - Payload mass fraction reduced for small scale launch vehicle (MEMS launch vehicle not a good idea)
  - Need cluster arrays of small scale thrusters on larger flight systems to take advantage of high T/W weight advantage of MEMS thrusters.
  - Small flight vehicle scale is good for nano RVs where vehicle wants to decelerate due to aerodynamic losses.

Payload Mass Fraction versus Launch Vehicle Mass

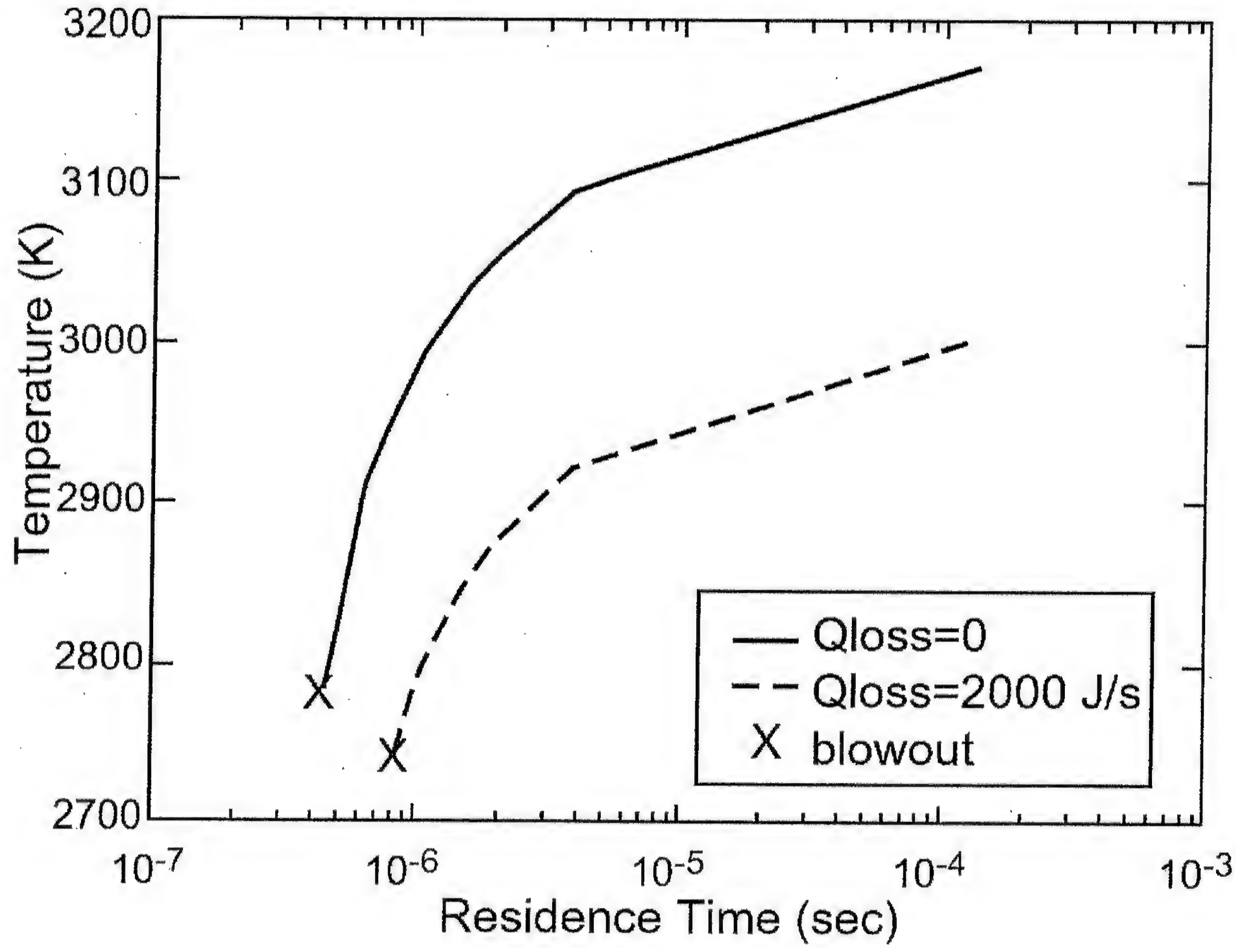


Effects of Air Drag on Launch Vehicle Performance (770 km Orbit/90 deg. Inclination/Ground Launched) (Francis, 1999)

Microthruster Combustion Residence Time Analysis

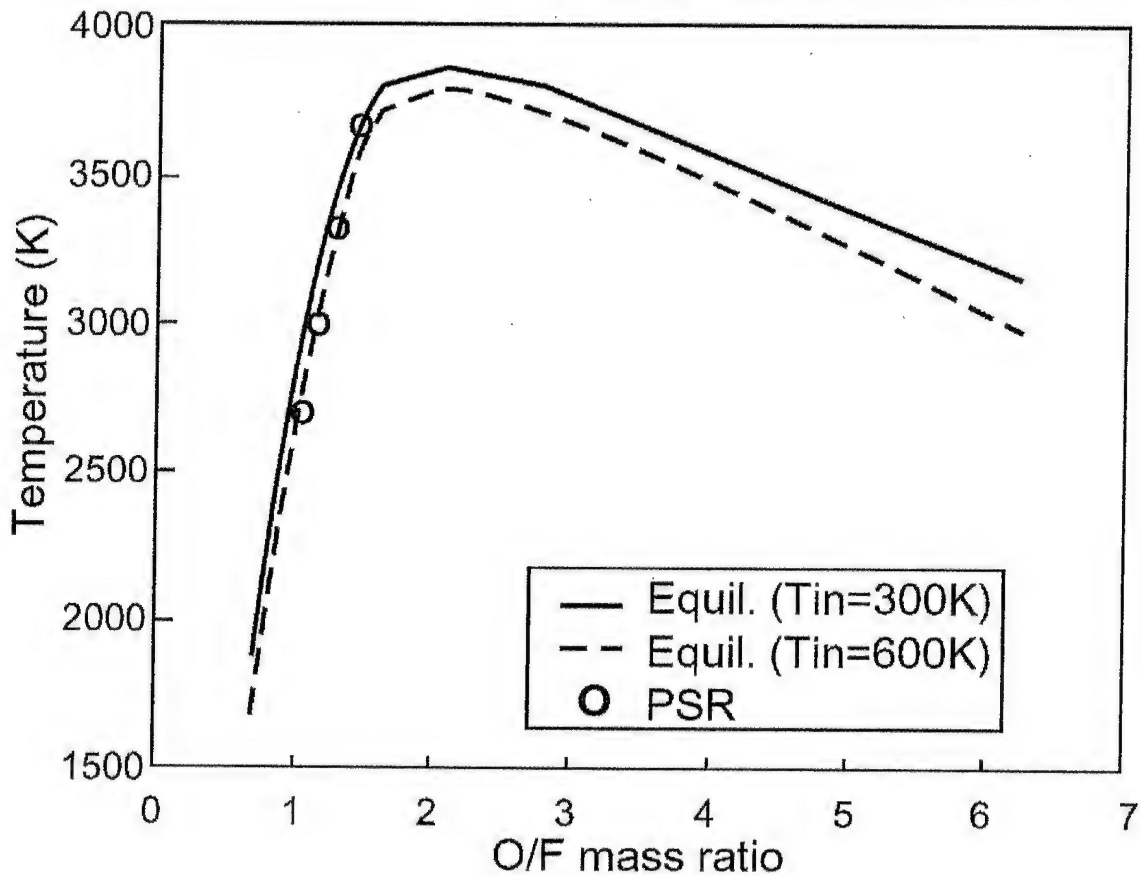
- Detailed chemical kinetics analysis of combustion residence time as a function of chamber pressure and oxidizer to fuel ratio
  - Data match more detailed theoretical combustion residence model done by MIT with more general AFRL/PRST bimolecular chemical kinetics combustion model
  - Use same procedure to data match MIT microthruster experimental results
- Shorter combustion residence occurs at lowest combustion temperature at fuel-rich blow out limit

MIT Combustion Analysis Results



Chemical Kinetics Residence Time for Ethanol and Oxygen (O.M. Al-Midani, 1998)

MIT Combustion Analysis Results-cont.



Combustion Chamber Equilibrium Temperatures for Different O/F Ratios for Ethanol and Oxygen (O.M. Al-Midani, 1998)

AFRL Bimolecular Chemical Kinetics Combustion Model

- Combustion residence time proportional to Arrhenius activation energy (The lower the activation energy, the shorter the combustion residence time)
- This formed the basis of data matching the MIT combustion analysis with a more general bimolecular second-order chemical kinetics combustion model

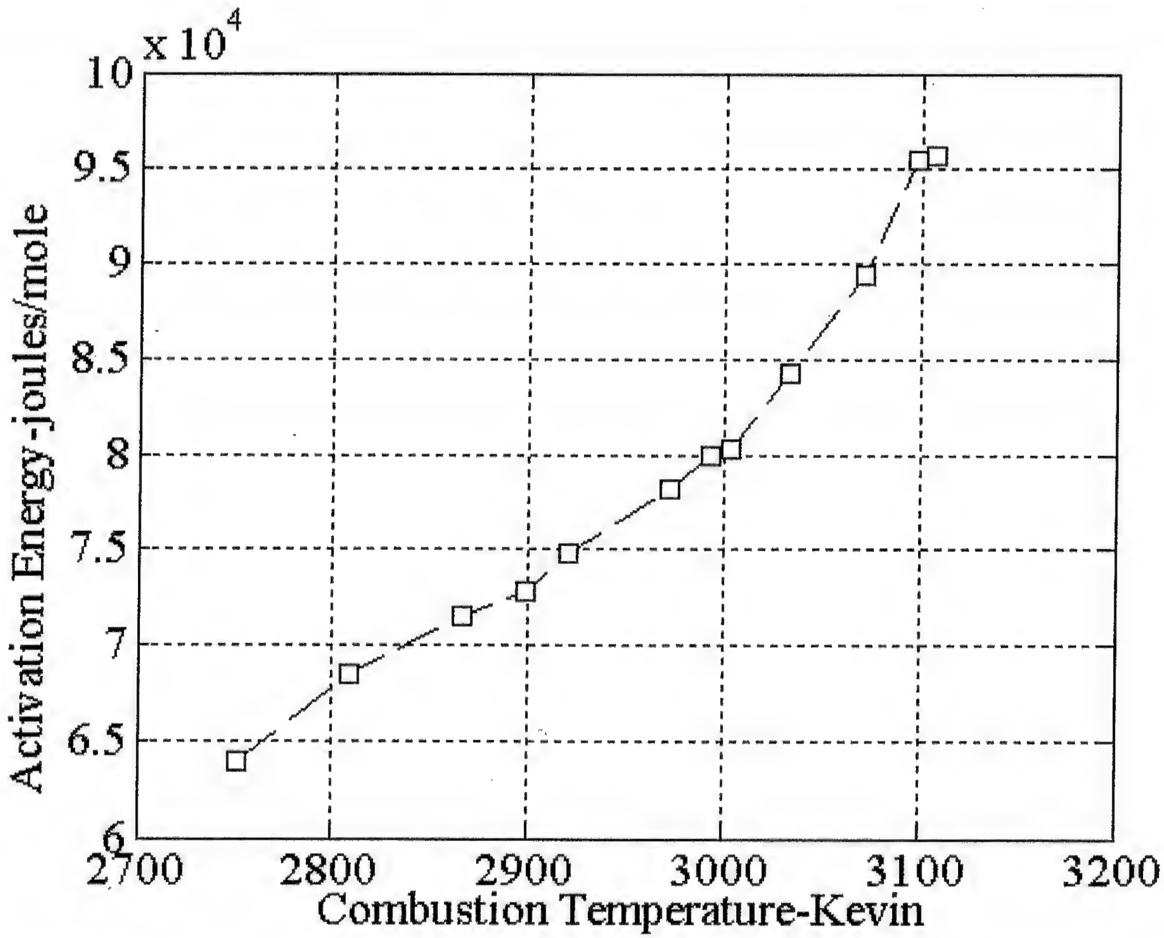
AFRL Bimolecular Chemical Kinetics Combustion Model-Cont.

- **PRST chemical kinetics combustion model final analytical solution**

$$\tau_{comb} \approx 6 / \left(N_{Ao} \cdot b \cdot k_{AB}\right)$$

  - **Combustion residence time inversely proportional to pressure and proportional to Arrhenius activation energy**
  - **Was applied to MIT experimental results also.**

AFRL Activation Energy Data Match



Activation Energy versus Combustion Temperature for Ethanol/Oxygen

Determining Minimum Chamber Size with MIT Data and PRST Bimolecular Chemical Kinetics Model

- **The procedure to calculating shortest possible combustion residence time is selecting a fuel rich O/F ratio that minimizes the combustion temperature or activation energy, and which is still above the fuel-rich blow-out limit**

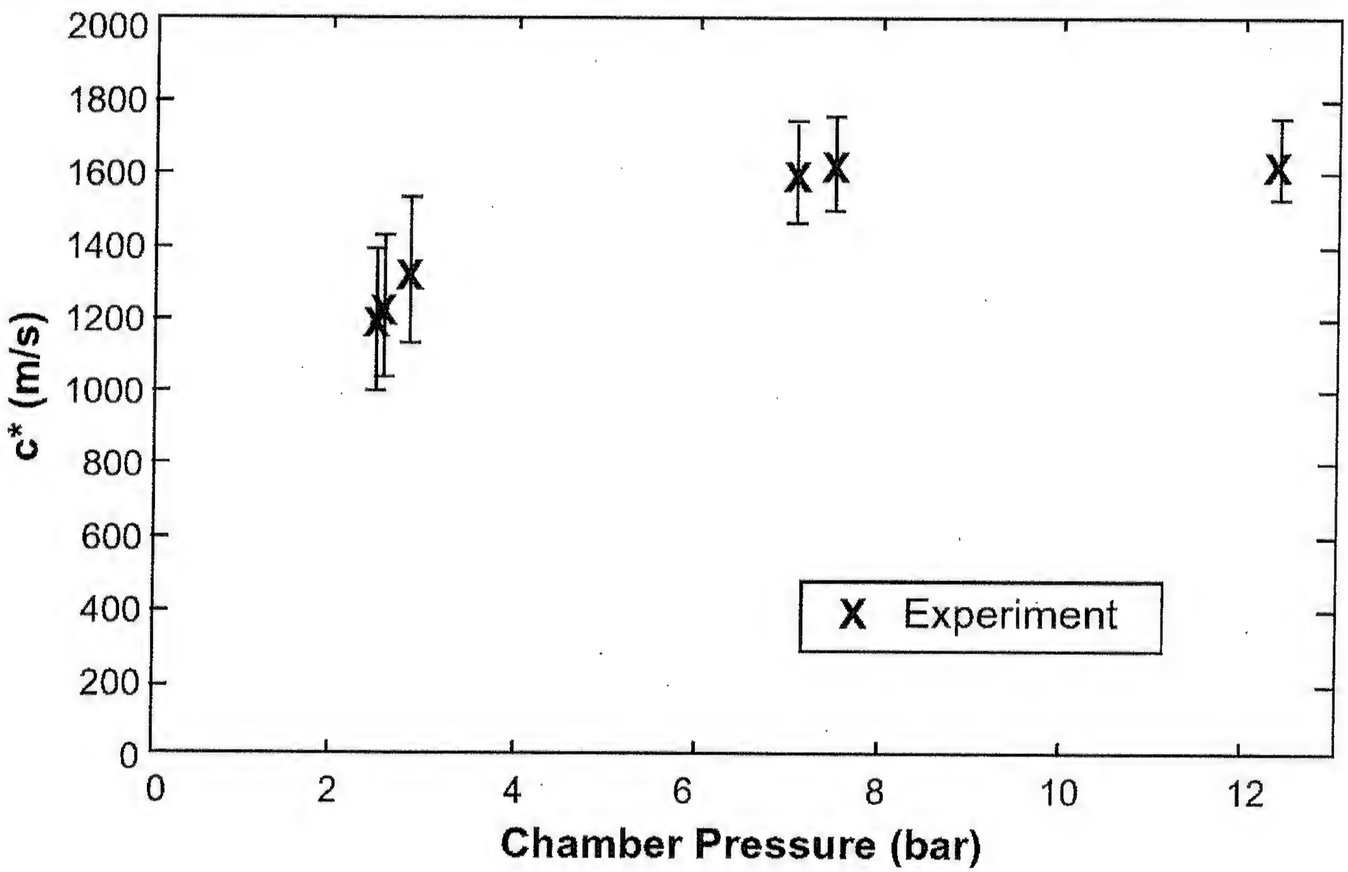
Determining Minimum Chamber Size with MIT Data and PRST Bimolecular Chemical Kinetics Model-Cont.

- Chamber residence time is independent of chamber pressure
  - 0.1 msec for MIT engine
- Final combustion residence time results are determined by setting combustion residence time equal to chamber residence time and plotting up minimum chamber pressure for complete combustion versus engine characteristic length

Determining Minimum Chamber Size with MIT Data and PRST Bimolecular Chemical Kinetics Model

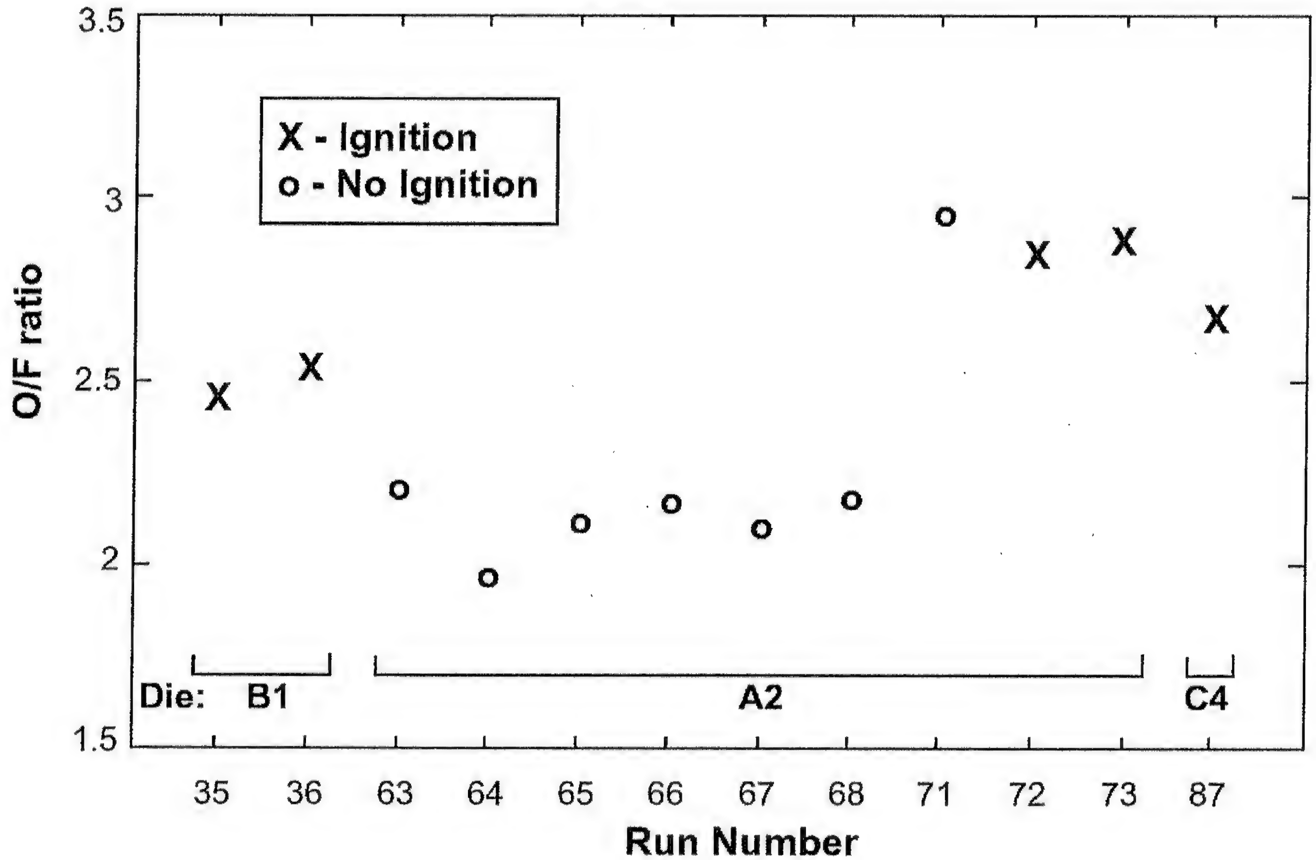
- The procedure to matching the MIT experimental data is determining the chamber pressure where exhaust velocity is maximized, then determine O/F ratio at that test point, then estimating Arrhenius activation energy for those conditions at chamber residence time equal to combustion residence time

MIT Measurement of Characteristic Velocity for Microrocket



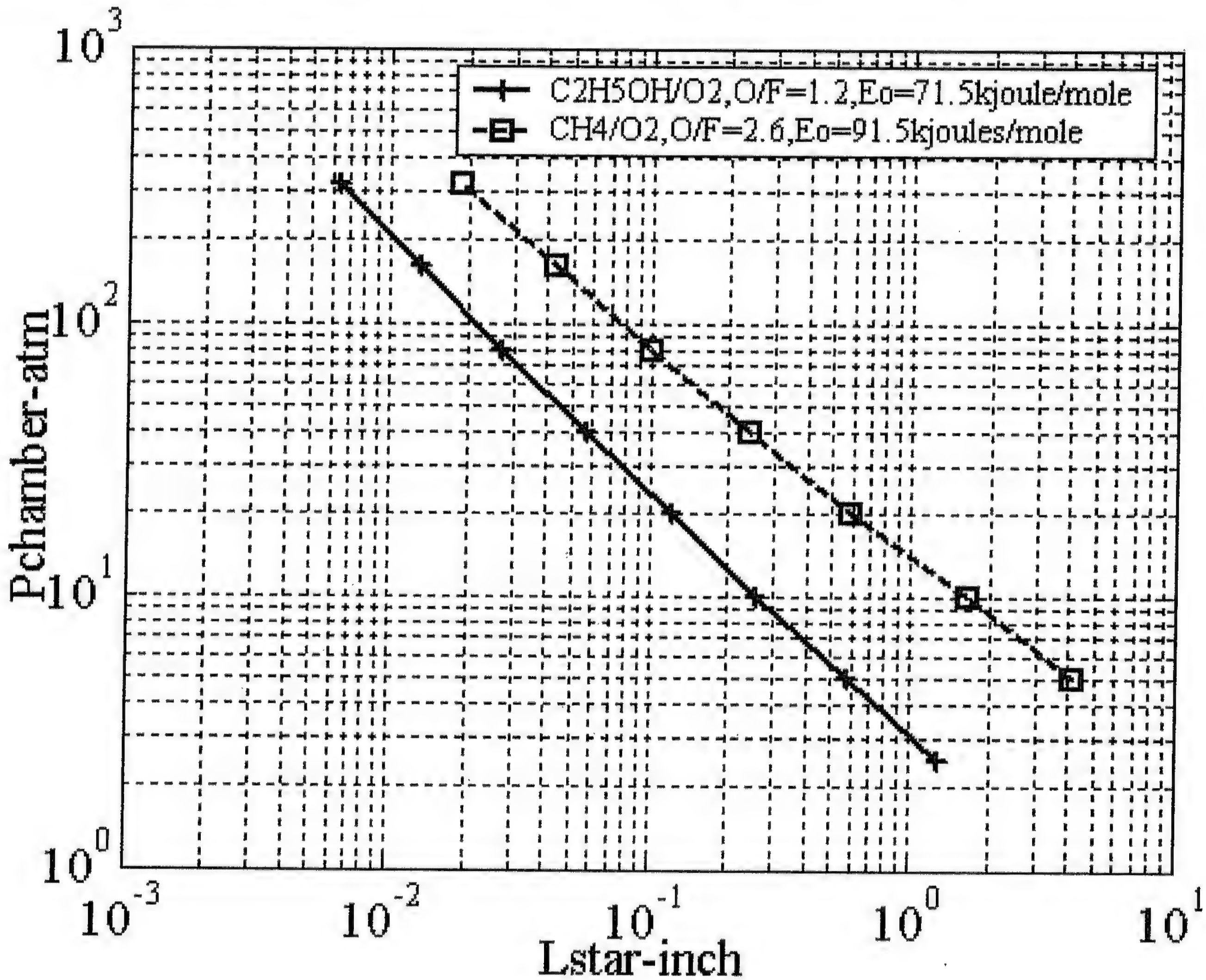
Experimental Measurement of Characteristic Velocity Versus Chamber Pressure for MIT Microrocket (London, 2001)

MIT Microthruster O/F Ratio



MIT Microrocket Ignition Results for Methane and Oxygen (London, 2001)

Minimum Chamber Length versus Chamber Pressure for Complete Combustion



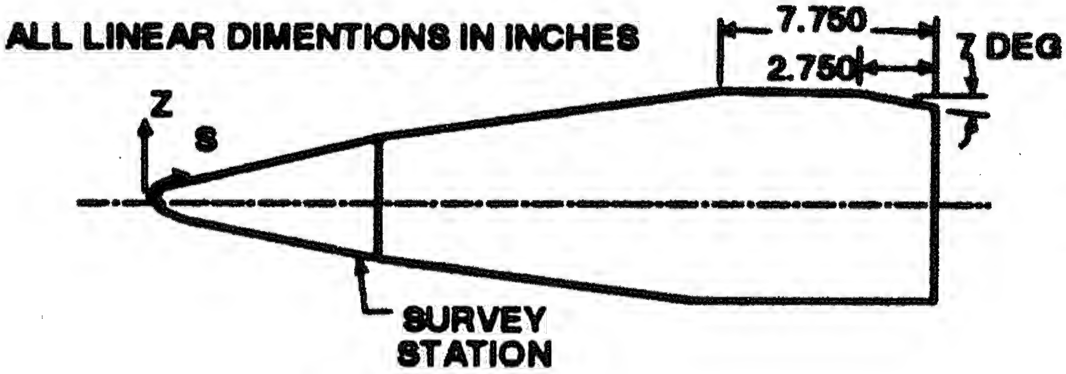
Specific Impulse Performance at Reduced Engine Characteristic Lengths

- The resulting specific impulse from TEP analysis was 345 seconds for methane and oxygen and 301 seconds for ethanol and oxygen at the chamber pressures required for complete combustion at the reduced engine characteristic lengths

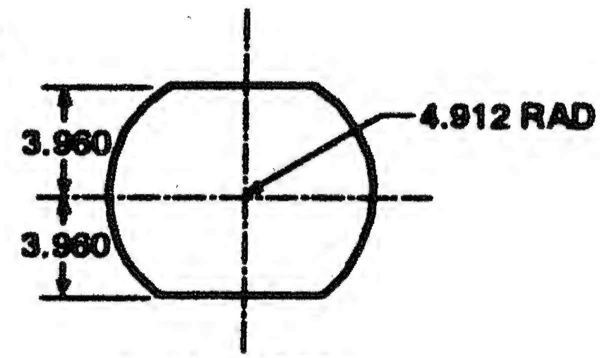
Application of High-T/W ratio Bipropellant TVC to Reentry Vehicles thru Micro-miniaturization

- **Apply simplified RCS total impulse analysis to full-scale maneuvering RV and a small scale nano RV**
  - **Control flap regions are replaced with RCS thruster arrays**
  - **Nano RV requires small RCS jets to get targeting accuracy**

Maneuvering RV Details

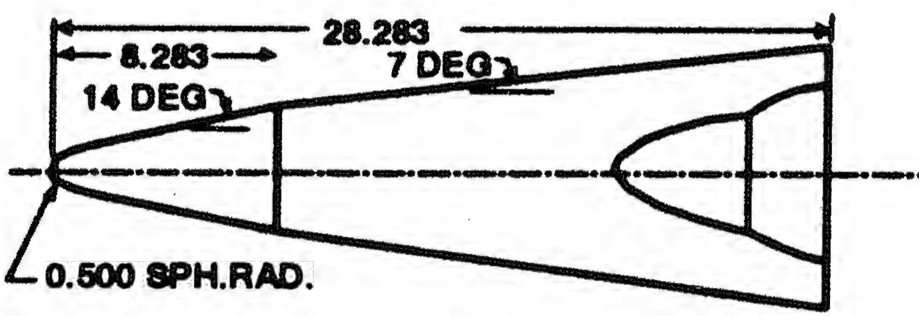


SIDE VIEW



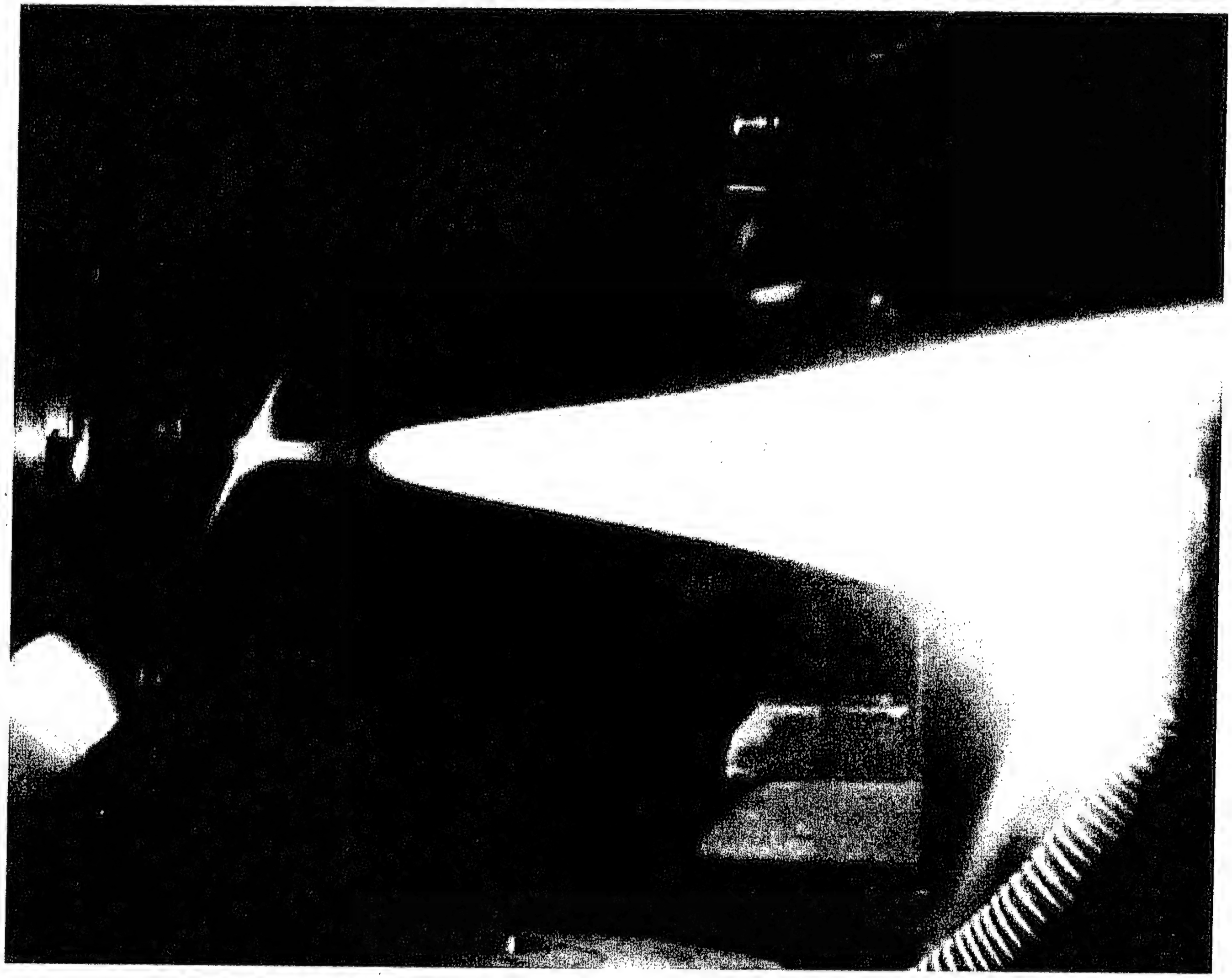
A. GEOMETRY

END VIEW
LOOKING UPSTREAM



TOP VIEW

Nano Reentry Vehicle (Haldeman, 1986)



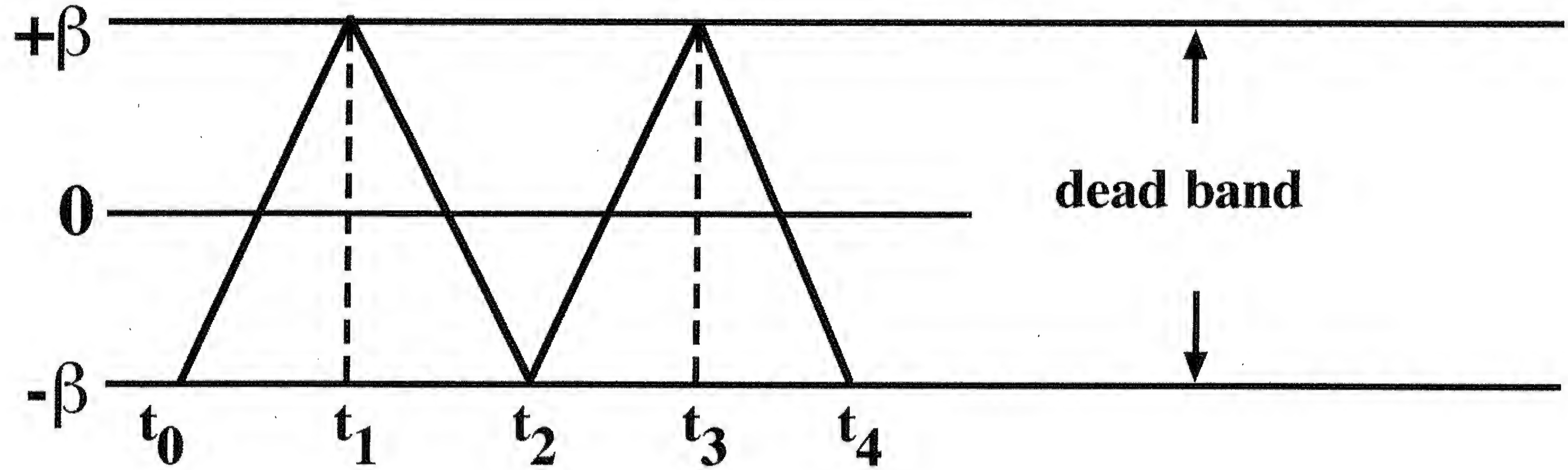
Application of High-T/W ratio Bipropellant TVC to Reentry Vehicles thru Micro-miniaturization

- **RCS analysis uses dead-band tolerance limit cycle analysis to determine RCS propellant consumption rate**

$$\dot{W}_p = \frac{I^2 \cdot L}{4 \cdot J_x \cdot I_{sp} \cdot \beta}$$

  - **Similar to satellite station-keeping TVC propellant consumption rate calculation**

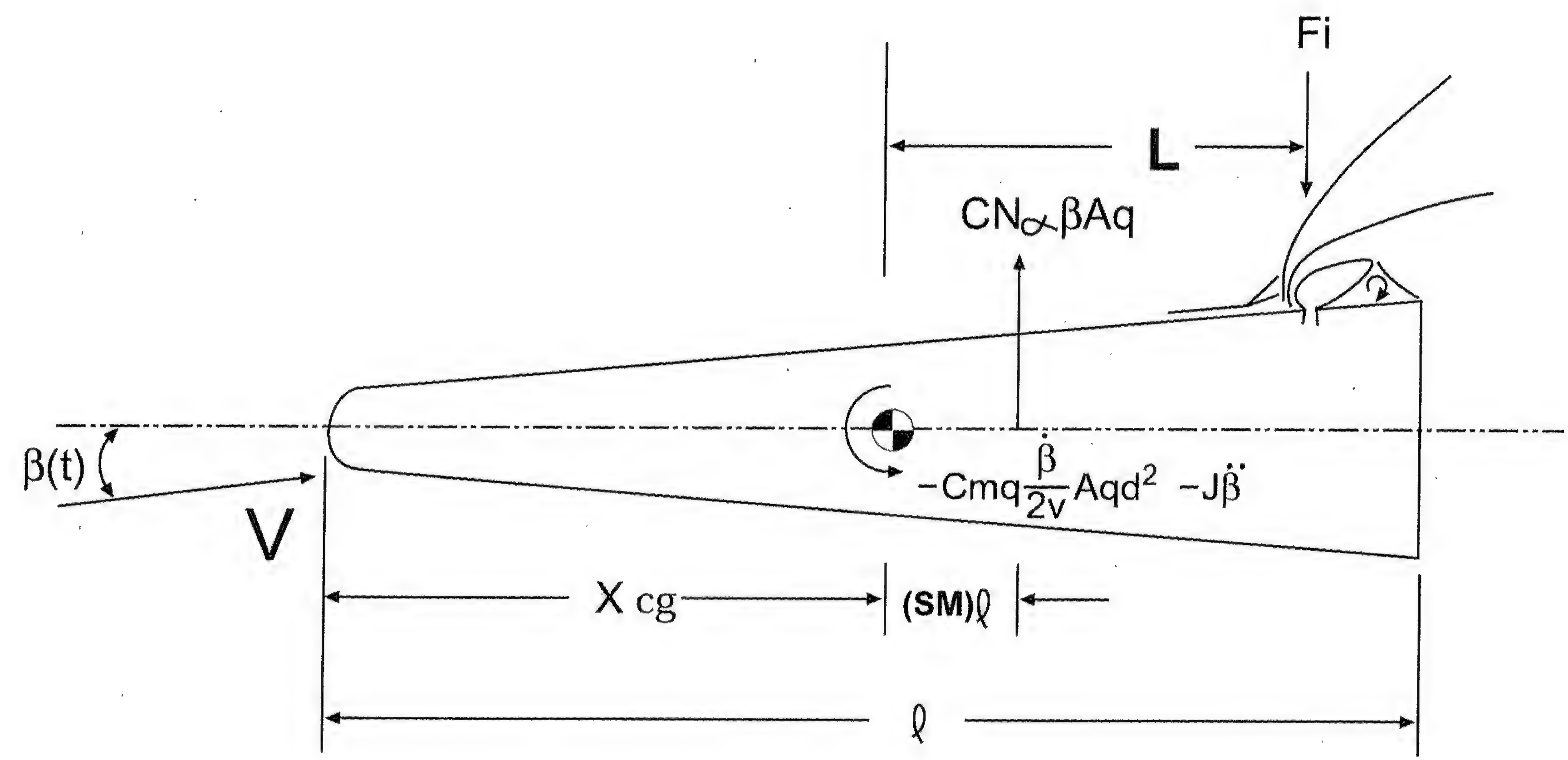
Reentry Vehicle Dead-Band Motion (Pohl, 1965)



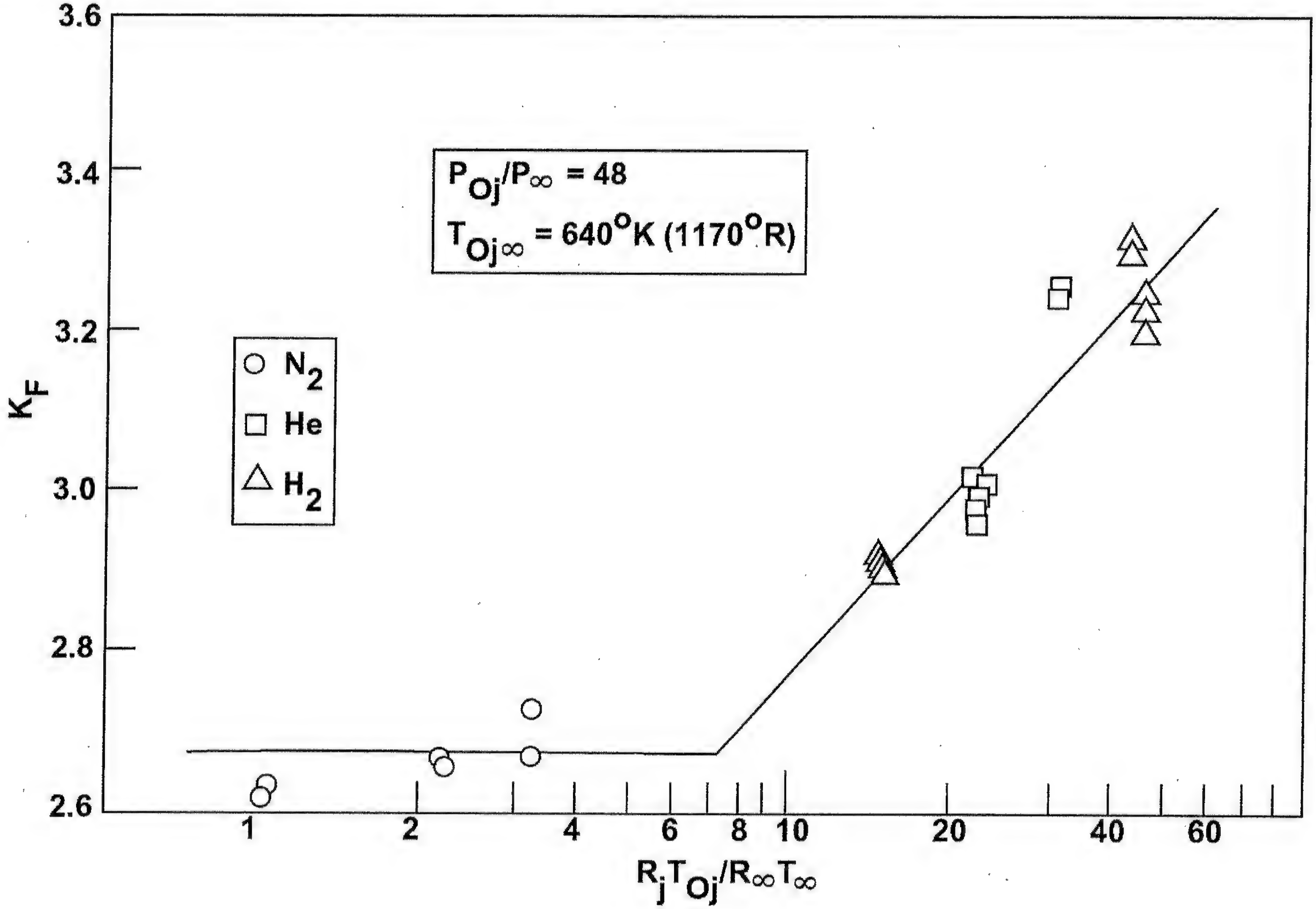
Application of High-T/W ratio Bipropellant TVC to Reentry Vehicles thru Micro-miniaturization-cont.

- Place RV aerodynamic center at center of gravity to minimize RCS propellant consumption
- RCS jet very effective due to constructive thrust augmentation due to freestream interaction with RCS jet plume

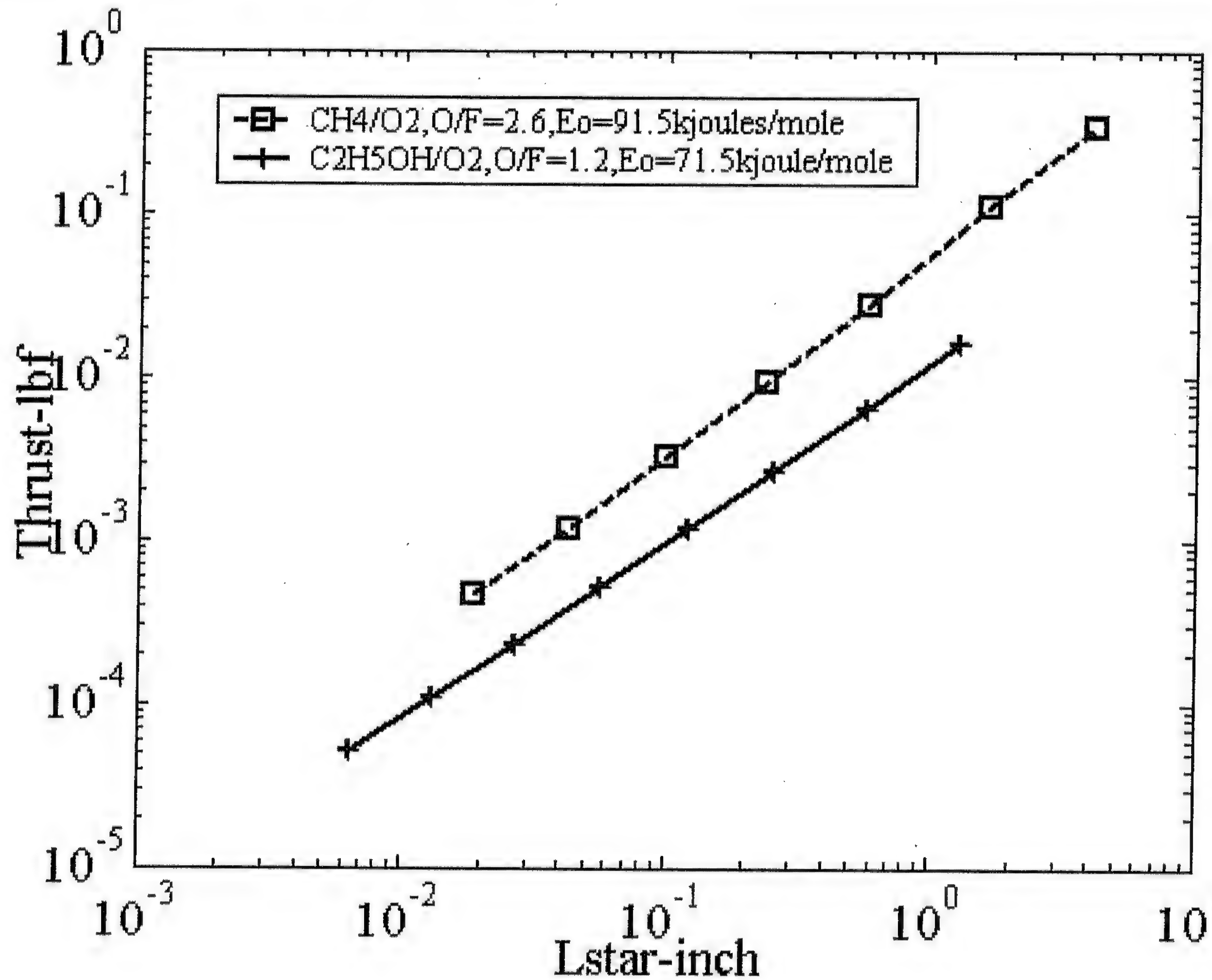
Reentry Vehicle Reaction Control System Forces and Moments



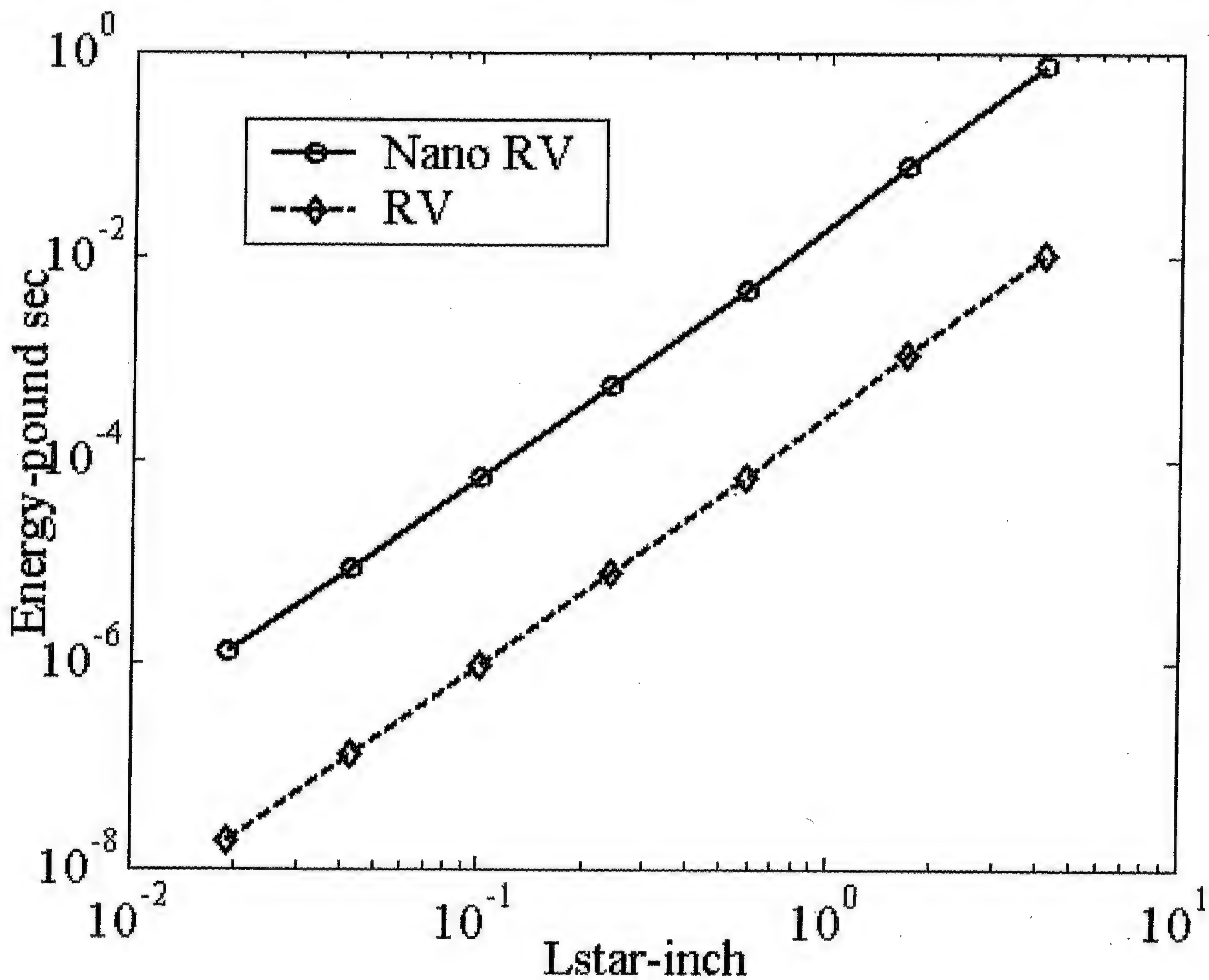
Dependence of the Jet Thrust Amplification Factor, K_f, on Temperature and Molecular Weight



Minimum Obtainable Microjet Thrust versus Chamber Characteristic Length



RV RCS Mission Impulse Requirements for Dead-Band Targeting Motion



Conclusions

- MEMS small-scale vehicles make excellent missile payloads such as MEMS satellites or nano RVs
  - Excellent for nano RV where the enhanced drag characteristics of a reduced mass MEMS vehicle is an advantage during reentry
  - Nano RVs decelerate more quickly then full-scale RVs allowing more time below plasma shielding altitude for target acquisition and seeking
  - Counter productive to develop a reduced scale launch vehicle because of the reduced payload mass fraction resulting from increased aerodynamic losses at reduced scales.

Conclusions-cont.

- To take advantage of the high thrust to weight ratio performance enhancement of small scale rocket engines, they should be clustered into larger arrays propelling larger vehicles
  - Reduction in propulsive engine weight in relation to the overall vehicle weight would be realized without a corresponding loss in payload mass fraction due to the enhanced effects of small scale vehicle drag losses
- RCS propellant consumption is reduced as a result of reducing minimum impulse bit

Caveats with Using MEMS Combustion Results (Ideas for Future Work)

- Ideally want hypergolic propellant for intermittent duty TVC
  - Hypergolic or spontaneous ignition delay, and possibly spark ignition delay would have to be demonstrated at elevated chamber pressures in order to achieve steady-state combustion at smaller and smaller engine scales.
    - Would be excellent follow-on combustion analysis to add to the previous combustion residence time analysis.
    - Solution is fundamentally similar to the combustion residence time analysis problem

Ideas for Future Work-cont.

- **MIT demonstrated gaseous bipropellant injector mixing prior to combustion and for nonhypergolic propellants**
  - **Gaseous bipropellant injection may be also required for hypergolic ignition to be successful at reduced engine characteristic lengths**

Ideas for Future Work-cont.

- Mixing time scales have not been demonstrated for liquid to liquid bipropellant injection
  - Droplet evaporization times at reduced engine characteristic lengths would be good follow-up work
- Regent cooling for intermittent duty microthruster to maintain high Isp operation at reduced engine characteristic lengths

Acknowledgment

- Like to acknowledge the help of Prof. Alan Epstein in providing critical MEMS engine design and performance characteristics without which this technical effort would have been very difficult to complete.
- MIT Gas Turbine Lab design and demonstration of a MEMS bipropellant microthruster was a major breakthrough in the understanding of rocket engine combustion phenomena at reduced residence times and engine scales